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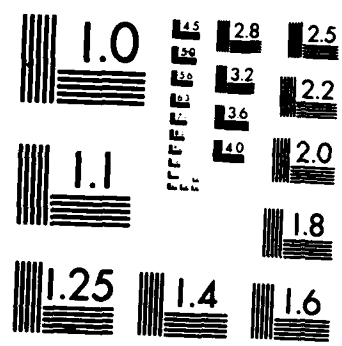

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THE PERFORMANCE OF A MULTI-CHANNEL N:M DETECTOR USING CFAR AGAINST WHITE NOISE JAMMING

by

Robert W. Herring, Ross M. Turner, Eric K.L.Hung

This work was performed for and under the sponsorship of the Department of National Defence, Chief of Research and Development.

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CRC Technical Note No. 719
Ottawa, January 1984

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The Performance of a Multi-Channel N:M Detector Using CFAR Against White Noise Jamming

Robert W. Herring
Ross M. Turner
Eric K.L. Hung

ABSTRACT

The detection performance of an N:M (N out of M) detector radiating on M independent channels and using CFAR in the individual channels is analyzed in the presence of white noise jamming with Rayleigh amplitude statistics. The particular case examined is for an M=10 channel system with from zero to 10 channels equally jammed, detecting a target having Rayleigh channel-to-channel amplitude statistics and equal average powers in all channels. The design P_D is 90% and the design P_{FA} is 10^{-6}. It is shown that under these conditions the optimum choice for N is always less than or equal to 3, with small values being most appropriate for situations with many channels being heavily jammed.

1. INTRODUCTION

In a previous report [1] the performance of an adaptive noncoherent processor (ANCP) system for multichannel radars was analyzed. The ANCP operates by estimating the noise environment in each active channel of the radar, adaptively adjusting the gain of each channel, and then non-coherently combining the outputs of the channels before executing a single target present/non-present threshold detection. In implementation the ANCP is similar to the ratio detector of Trunk and Hughes [2].

An apparently attractive alternative to the ANCP might be the N:M (N out M) detector with a constant false-alarm rate (CFAR) threshold detector in each of the M channels. An N:M detector reports a target detection when N or more of the M active channels exceed their detection thresholds. The use of a CFAR procedure prevents any jammed or otherwise noisy channels from dominating the false alarm performance.

In this note the theoretical performance of an N:M detector operating under the same conditions as the ANCP of [1] is investigated using closed-form techniques. It is assumed that the target statistics on a channel-to-channel basis are uncorrelated and Rayleigh (Swerling's Case 2), with equal average signal powers in all channels. It is also assumed that the noise and jamming powers are white with Rayleigh amplitude statistics and with no channel-to-channel correlation. However, the average noise and jamming powers may differ in the various channels. The performance of this detector has also been investigated by Trunk and Hughes [2], using simulation methods.

The theory of the N:M detector is analyzed in Section 2. It is shown that if a CFAR scheme is used so that the probability of false alarm is the same in all channels, the operation of the N:M detector is described by the binomial distribution function [3]. The analysis is then extended to include the case of detection when the probabilities of detection in the M channels differ due to the effects of jamming. For simplicity the analysis is restricted to the case of equal jamming powers in all the jammed channels.

Section 3 contains results for the particular case of M=10 channels, a system probability of false alarm (P_{FA}) of 10^{-6} and a system probability of target detection (P_D) of 90%. These parameters were chosen to be consistent with [1]. It is shown that in the presence of jamming it is unwise to choose M too large, because of the likelihood of having to make reliable detections in the jammed channels.

Finally, Section 4 summarizes the results and puts them in context with those of [1].

2. THEORY

2.1 Introduction

An N:M detector is a system comprising M channels, each of which has its own threshold detector. If at any instant N or more of these channels exceed their individual detection thresholds, a target detection is declared. Thus, an N:M detector is a double-threshold system, with the individual channel detectors serving as hard-limiting input devices to a second stage which is essentially a counter.

In the following analysis it is assumed that there are two classes of channels, jammed and unjammed. The number of jammed channels, J, can range from 0 to M. To simplify the analysis, it is assumed that the average noise powers in the channels of each class are mutually identical.

The problem of analyzing false-alarm and target-detection performance can be broken into the usual two parts. The first is to determine the threshold levels in the jammed and unjammed channels required to give the specified P_{FA} at the output of the second detector of the N:M system. These thresholds are dependent on the noise and jamming powers, and on N. Second, it is necessary to determine S, the unjammed single-channel SNR required to gove the specified P_D at the output of the N:M detector.

2.2 Probability of False Alarm

To proceed, it is necessary to relate the probability of N or more single-channel false alarms to the probability of a false alarm in any single channel. To simplify matters it is assumed that a CFAR scheme is used in each channel, so that the probability of single-channel false alarm, P_{fa}, is the same in both the jammed and unjammed channels.

With no channel-to-channel correlation and equal single-channel

probabilities of false alarm in all channels, the probability of N or more simultaneous single-channel false alarms is given by the binomial distribution [3]:

$$P_{FA} = \sum_{n=N}^{M} \binom{M}{n} p_{fa}^{\,n} (1-p_{fa})^{M-n} \tag{1}$$

where P_{FA} is the system probability of false alarm.

To determine the individual channel thresholds, it is first necessary to specify P_{FA}, M and N in Eqn. (1), and then solve for p_{fa}. This can be done iteratively. The threshold is then determined on the basis of the required values of p_{fa} and the particular statistical distribution assumed for the noise and jamming powers. The solution to this problem for the particular case of Gaussian noise and Gaussian jamming, and a cell-averaging CFAR system using L samples in each channel is given in the Appendix.

2.3 Probability of Detection

Setting the threshold in each channel determines the single-channel probability of detection for that channel when the target signal is present. (It is assumed that the average signal powers in all the channels are the same.) However, because there are two classes of channels, jammed and unjammed, the SNRs and thus the single-channel probabilities of detection are different for the two classes.

The probability of target detection, P_D, is the probability of $n \geq N$ simultaneous single-channel target detections. For the present situation, P_D can be formulated in general terms as

$$P_D = P_1(N) + \sum_{q=\mathrm{Max}\{1,N-(M-J)\}}^{\min(N,J)} P_2(q)\, P_3(N-q) \tag{2}$$

where

$$P_1(N) = \Pr[N \leqslant n \leqslant (M-J) \text{ detections in the } (M-J) \text{ unjammed channels}], \tag{3}$$

$$P_2(q) = \Pr[q \leqslant n \leqslant J \text{ detections in the J jammed channels}], \tag{4}$$

and

$$P_3(N-q) = \Pr[\text{exactly } (N-q) \text{ detections in the } (M-J) \text{ unjammed channels}]. \tag{5}$$

It should be noted that P_1 is identically zero if N is greater than the number of unjammed channels; P_2 is identically zero if $q > j$; and P_3 is identically zero if $(N-q) < 0$ or if $(N-q) > (M-J)$. These constraints lead to the limits on the summation indicated in Eqn. (2).

Because of the assumed absence of channel-to-channel correlation, the Eqns. (3-5) can be expressed in terms of the binomial distribution. Thus,

$$P_1(N) = \begin{cases} \sum_{n=N}^{M-J} \binom{M-J}{n} p_u^{\,n}(1-p_u)^{M-J-n} & (N \leq M-J) \\ 0 & (N > M-J) \end{cases} \tag{6}$$

where p_u is the single-channel probability of detection in an unjammed channel;

$$P_2(q) = \begin{cases} \sum_{n=q}^{J} \binom{J}{n} p_j (1-p_j)^{J-n} & (q \leq J) \\ 0 & (q > J) \end{cases} \tag{7}$$

where p_j is the single-channel probability of detection in a jammed channel; and

$$P_3(N-q) = \begin{cases} \binom{M-J}{N-q} p_u^{\,N-q}(1-p_u)^{(M-J)-(N-q)} & (N-(M-J) \leq q \leq N) \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

It is shown in the Appendix how to computer p_u and p_j (Eqns. (A.10 and (A.11)) in terms of the average signal power S (normalized in terms of the unjammed channel noise power) and the unjammed and jammed channel thresholds.

3. RESULTS

3.1 Introduction

To retain consistency with [1], the detection performance of N:M systems with M=10 channels, a system P_{FA} of 10^{-6} and a system P_D of 90% were analyzed in the presence of various levels of jamming. For simplicity it was assumed that the jamming power in each of the jammed channels was the same. It was further assumed that the noise and jamming were white with Rayleigh amplitude statistics, the target signal amplitude statistics were also Rayleigh, and there was no channel-to-channel correlation of either the noise, the jamming or the signal. Under these assumptions, the required single-channel signal level S was determined for various jamming powers as the number of jammed channels, J, was varied from 0 to 10.

In section 3.2 the results for the case of no external jamming are given, and it is shown how there is an apparent optimum value for N. In Section 3.3 results are given for the case of external jamming, and it is shown that the apparently optimum value for N of Section 3.2 is actually an upper limit.

3.2 No Jamming

Fig. 1 shows the required single-channel signal power, S, as a function of N for the case of no jamming or external interference. Three curves, labelled L=16, L=32 and L=∞, are shown, where L is the number of noise samples used to estimate the single-channel CFAR thresholds. L=∞ corresponds to exact or prior knowledge of the noise powers.

As N varies from 1 to 10, the CFAR loss incurred due to using estimated rather than exact threshold ranges from 3.3. dB to 0.2 dB for L=16. The echo energy S is minimized when N=3 for L=∞ or L=32, and when N=4 for L=16. This appears to suggest choices for N of 4 or less would provide the best detection performance under most circumstances. The matter of optimum choice for N is discussed further in Section 3.3 below.

The behaviour of the curves in Fig. 1 can be explained as follows. Table 1 shows the required single-channel probabilities of false alarm, p_{fa}, and unjammed single-channel probabilities of detection p_u, as a function of N for the specified values of M, P_{FA} and P_D. These values of p_{fa} and p_u were found by iteratively solving Eqns. (1) and (6), respectively, remembering that no jamming means J=0.

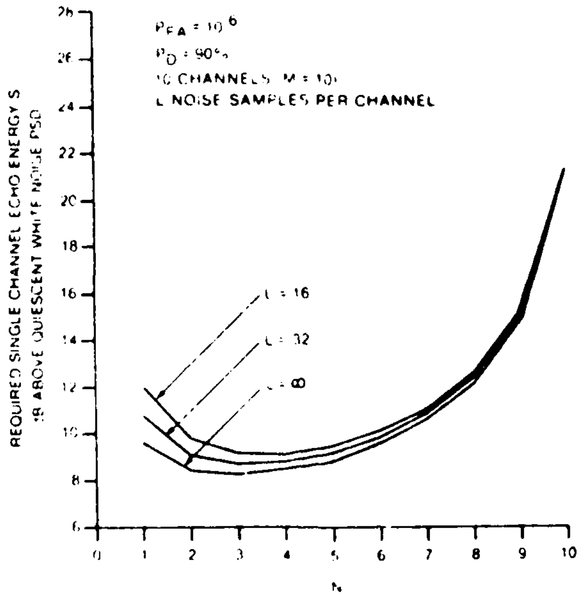

Figure 1 - **Required echo energy as a function of L and N for no external jamming.**

$M=10$	$P_{FA} = 10^{-6}$	$P_D = 90\%$
N	p_{fa}	p_u
1	1.000×10^{-7}	20.6%
2	1.450×10^{-4}	33.7%
3	2.037×10^{-3}	45.0%
4	8.385×10^{-3}	55.2%
5	2.126×10^{-2}	65.6%
6	4.203×10^{-2}	73.3%
7	7.211×10^{-2}	81.2%
8	1.135×10^{-1}	88.4%
9	1.699×10^{-1}	94.55%
10	2.512×10^{-1}	99.95%

Table 1 **Required single-channel probabilities for false alarm (p_{fa}) and detection (p_u) as a function of N.**

For small values of N the single-channel thresholds must be set higher in order to provide the required small values of p_{fa}. Moreover, for small values of L the threshold must be set even higher, to compensate for the uncertainty in estimating the noise power using only a small number of samples. (This explains why the CFAR loss is greater for smaller values of p_{fa}.) However, when N is small, only moderate values of p_u are needed to ensure that N or more channels will detect the target signal 90% of the time. Even for relatively high thresholds, modest values of S will yield the required p_u.

As N is increased, P_{fa} decreases and the threshold drops. Conversely, the required values of p_u increase to rather large values for $N > 8$. These high values of p_u are necessary to ensure that at least N channels detect the target 90% of the time. Such high values for p_u can require extremely large values for S.

3.3 Jamming

Figs. 2-5 show the dependence of S on the number of jammed channels and the total jamming-plus-noise power, for values of N ranging from 1 to 4. These figures are analogous to Fig. 5 of [1], except that here there is the additional freedom of choosing the value of N. Each of Figs. 2-5 shows how, for a particular choice of N, the required value for S is increased as progressively more channels are jammed, or as the noise level in the jammed channels is increased.

As N is increased from 1 to 4, two phenomena can be observed. The first is the drop in S for J=0 as N is increased. This is the same effect as shown in Fig. 1, where it is also seen that S increases for N greater than 4. The second, and more interesting phenomenon is what happens under strong jamming when the number of unjammed channels is less than N.

When the number of unjammed channels is less than N, it is necessary to have one or more single-channel detections in jammed channels. This requirement forces a sharp increase in S, in order to raise the SNR in the jammed channels sufficiently to provide an adequate value of single-channel probability of detection in the jammed channels.

Detailed comparison of Figs. 2-5 shows the following for jamming plus noise powers of 20 dB or greater. For J in the range 7 to 9, choosing N=1 minimizes the required values for S. (Choosing N=3 for J=6 and 20 dB or 30 dB jamming plus noise raises the required values for S by 2.0 dB, choosing N=1 costs only 0.3 dB. Choosing N=3 for J=4 costs 0.2 dB; choosing N=1 for J=1 costs 1.4 dB). For J in the range 1 to 3, choosing N=3 minimizes the required values for S. (Choosing N=2 for J=1 costs 0.3 dB; choosing N=1 for J=1 costs 2.5 dB.)

For jamming plus noise levels of 10 dB or less the situation is slightly different. Detailed comparison of the Figs. 2-5 shows that the choice N=3 is almost always optimum, except for J in the range 4 to 7 for jamming plus noise levels of 10 dB, where the choice N=2 is superior by not more than 0.5 dB. (Choosing N=1 for any value of J always costs less than 3 dB.) The optimum choices for N are summarized in Table 2. It is clear that choosing N greater than 4 is always suboptimum for white Rayleigh noise jamming and Rayleigh target statistics.

J \ N	Jamming + Noise	
	$\leq$ 10 dB	$\geq$ 20 dB
0	4	4
1	3	3
2	3	3
3	3	3
4	2	2
5	2	2
6	2	2
7	2	1
8	3	1
9	3	1
10	4	4

Table 2 **Optimum choices for N as a function of jammed channels and the total jamming plus noise power.**

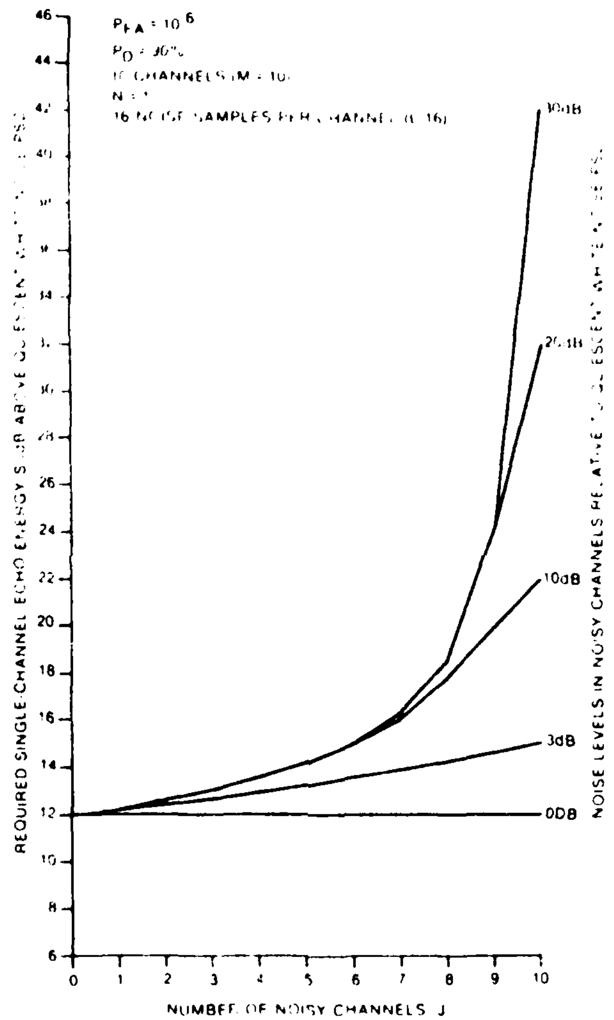

Figure 2 - **Required echo energy as a function of the number of jammed channels and the jammer plus noise power spectral density for N=1**

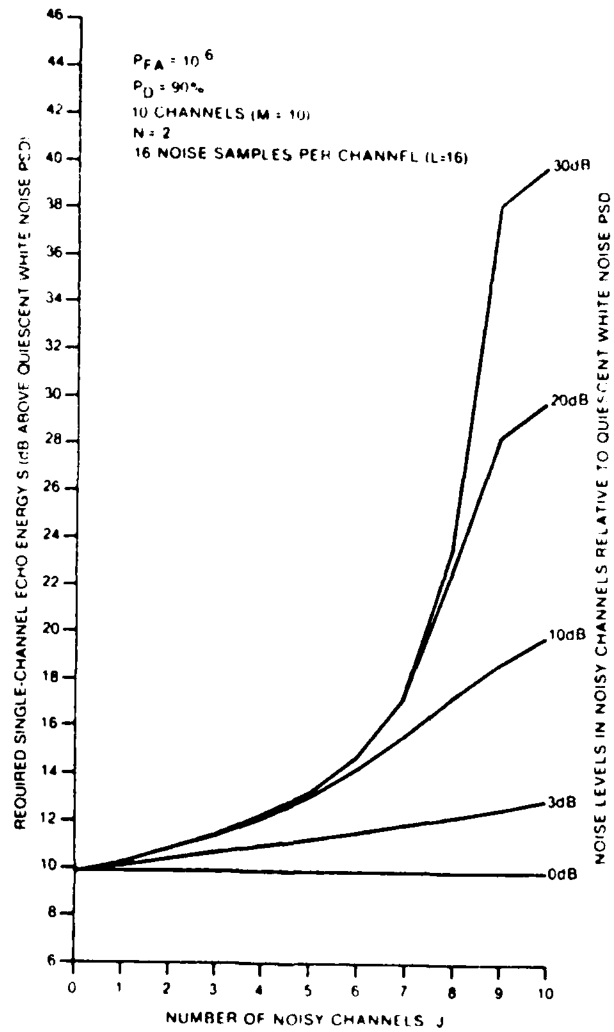

Figure 3 - **Required echo energy as a function of the number of jammed channels and the jammer plus noise power spectral density for N=2**

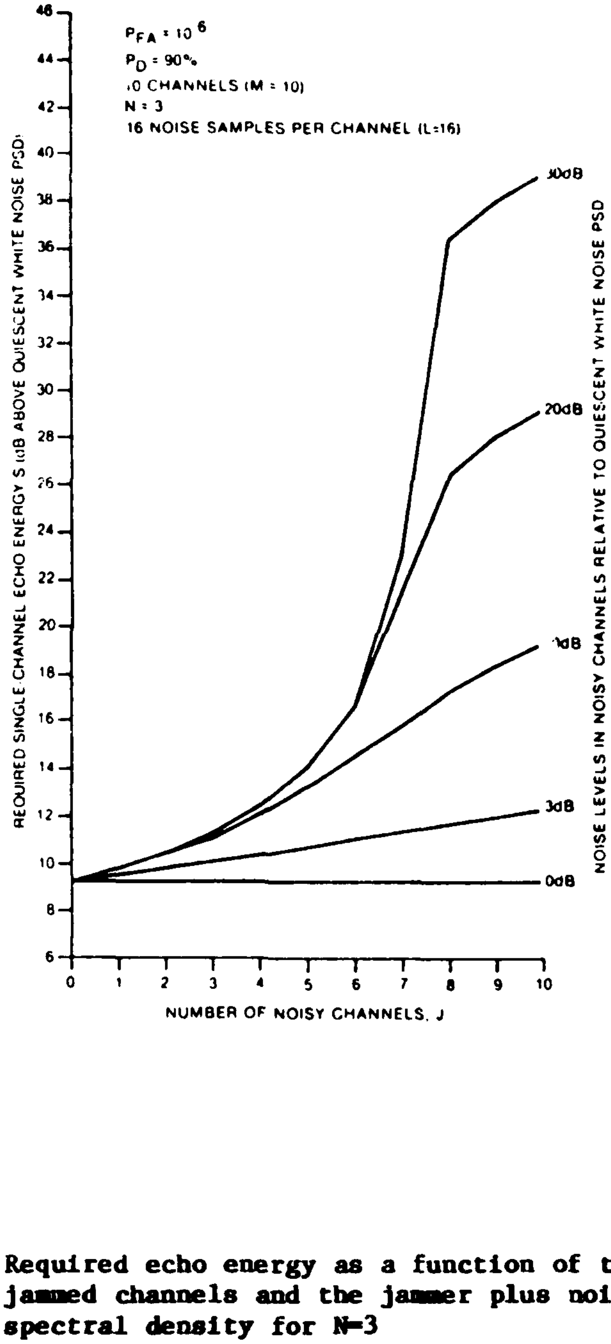

Figure 4 - **Required echo energy as a function of the number of jammed channels and the jammer plus noise power spectral density for N=3**

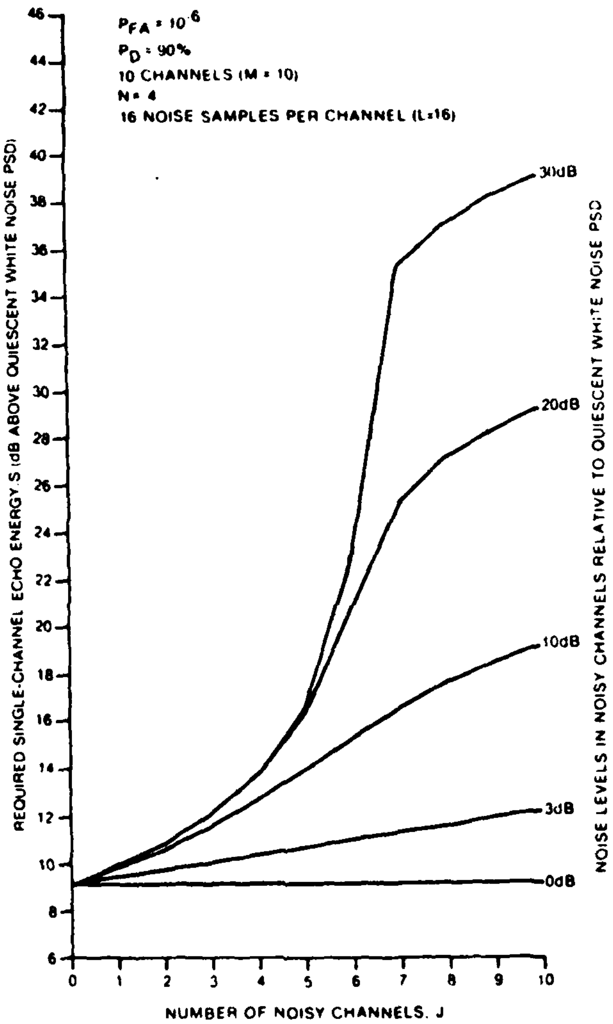

Figure 5 - **Required echo energy as a function of the number of jammed channels and the jammer plus noise power spectral density for N=4**

4. DISCUSSION AND SUMMARY

4.1 Discussion

The results of Section 3 show that, for an N:M system with M=10 channels operating in a white noise environment with Rayleigh amplitude statistics, the optimum value for N is never greater than 3. In the case of light jamming (less than 10 dB noise enhancement) the optimum choices for N are 3 or 2, but choosing N=1 is suboptimum by not more than 3 dB. In the case of heavy jamming (20 dB or greater noise enhancement) it is better to err by choosing N smaller rather than larger its optimum value, especially when the number of jammed channels approaches the total number of active channels in the system. In particular, when 9 of the 10 channels are jammed by 20 dB or more, the cost of choosing N=2 instead of the optimum N=1 is about 4 dB more than the number of dB by which the noise enhancement exceeds 20 dB (i.e., 14 dB loss for 30 dB noise enhancement in 9 channels).

Comparison of all the results of this report with those of [1] shows that the ANCP (or ratio detector) always offers superior detection performance, in agreement with the results of [2]. Specifically, the N:M system always requires at least 1.8 dB higher signal levels to produce equal detection performance, with this minimum value achieved only when all channels are jammed equally. Otherwise, the performance of the N:M system is even poorer relative to the ANCP. In addition, the N:M system suffers from the necessity of having to choose an optimum value for N which is directly independent on the noise and jamming powers, whereas the ANCP is indifferent to its environment. Thus the N:M system would require some sort of a control device to optimize its performance, whereas the slightly more complicated ANCP does not. For all these reasons, the ANCP appears to be the more attractive choice of the two noncoherent processors.

4.2 Summary

The case of an N:M detector with M=10 channels has been analyzed for the case of a cell-averaging CFAR in each channel for various levels of jamming power. For simplicity it was assumed that the jamming powers in all jammed channels were identical. The results have shown that when white noise jamming with Rayleigh amplitude statistics is present, it seems generally better to err by choosing N smaller than its optimum value in order to provide the best target-detection performance. It was also indicated that the adaptive noncoherent processor (ANCP) [1] operating under the same conditions provides superior target detection performance.

ACKNOWLEDGEMENT

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APPENDIX

Determination of the Single-Channel Probabilities of False Alarm and Detection

A.1 Introduction

It has been assumed that the jammer and receiver noise statistics are Rayleigh and that the target signal has equal average powers in all channels, Rayleigh statistics, and no channel-to-channel correlation. It will be assumed that the cell-averaging CFAR estimates the noise power in each channel by squaring and summing L noise samples, and then sets the channel detection threshold proportional to this sum.

Under these assumptions, the probability density function for the threshold is given by

$$p(t) = \frac{t^{L-1}}{(C\sigma_n^2)^L (L-1)!} \exp(-t/C\sigma_n^2) \qquad \text{(A.1)}$$

where t is the channel threshold, σ_n^2 is the total receiver plus jammer noise in the channel, and C is a constant of proportionality. The estimated threshold t is found by summing L noise samples Y_ℓ:

$$t = C \sum_{\ell=1}^{L} Y_\ell \qquad \text{(A.2)}$$

The average probability of single-channel threshold crossing, p_t, is then given by

$$p_t = \int_0^\infty \Pr[y > t|t]\ p(t)\ dt \qquad \text{(A.3)}$$

where $\Pr[y > t|t]$ is the probability that the squared output of the channel exceeds given value t. Under the assumptions of Section A.1, this probability is given by

$$\Pr[y > t|t] = \exp\ (-t/\sigma^2) \qquad \text{(A.4)}$$

where

$$\sigma^2 = \sigma_n^2 + S \qquad \text{(A.5)}$$

and S is the average single-channel signal power, if present.

Finally, substituting Eqns. (A.1), (A.4) and (A.5) into Eqn. (A.3) and solving leads to a closed-form expression for p_t:

$$p_t = \left| \frac{C}{1+S/\sigma_n^2} + 1 \right|^{-L} \quad (A.6)$$

A.2 Setting the Single-Channel Thresholds

To set the single-channel thresholds, it is necessary first to solve Eqn. (1) for the required single-channel probability of false alarm p_{fa} in terms of the system probability of false alarm P_{FA}. This can be done by any standard iterative technique, such as bisection. Having found p_{fa} to the desired degree of accuracy, it is a straightforward matter to determine the constant C from Eqn. (A.6) by setting S to zero and p_t to p_{fa} to get

$$C = 1/(p_{fa})^{\frac{1}{L}} - 1 \quad (A.7)$$

The expected value of the threshold can then be determined from Eqn. (A.2):

$$\langle t \rangle = C \sum_{\ell=1}^{L} Y_\ell \quad (A.8)$$

$$= CL\sigma_n^2$$

where $\langle \cdot \rangle$ denotes expected value.

A.3 Determining the Single-Channel Probabilities of Detection

It was stated in Section 2.3 that there are two classes of channel: jammed and unjammed. For consistency with [1], it will be assumed that the noise in the unjammed channels has been normalized to unit value so that

$$\sigma_n^2 \text{ (unjammed)} = 1 \quad (A.9)$$

and

$$\sigma_n^2 \text{ (jammed)} = 1 + X \quad (A.10)$$

where X is the additional noise power due to external jamming. It will also be assumed that S is the normalized target signal SNR in an unjammed channel.

Then from Eqns. (A.6) and (A.8) or (A.9), the single-channel probabilities of detection in the unjammed and jammed channels are given respectively by

$$P_u = \left[\frac{C}{1 + S} + 1 \right]^{-L} \tag{A.11}$$

and

$$P_j = \left[\frac{C}{1 + S/(1+X)} + 1 \right]^{-L} \tag{A.12}$$

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a document and could be helpful in cataloging the document. Key words should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context.

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